

# GRAVITATIONAL INFLUENCES ON FLAME PROPAGATION THROUGH NON-UNIFORM, PREMIXED GAS SYSTEMS

Fletcher J. Miller and John Easton, National Center for Microgravity Research, MS 110-3, Cleveland, OH, 44135-3191, [fletcher@grc.nasa.gov](mailto:fletcher@grc.nasa.gov)

Howard D. Ross, NASA Glenn Research Center, MS 500-115, Cleveland, OH 44135.

Anthony Marchese, Rowan University, Glassboro, NJ, 08028-1701

David Perry and Michael Kulis, Univ. of Akron, Akron, OH 44325-3601

## INTRODUCTION

Flame propagation through non-uniformly premixed (or layered) gases has importance both in useful combustion systems and in unintentional fires. As summarized previously [1,2,3], *non-uniform* premixed gas combustion receives scant attention compared to the more usual limiting cases of diffusion or *uniformly* premixed flames, especially regarding the role gravity plays. This paper summarizes our progress on furthering the knowledge of layered combustion, in which a fuel concentration gradient exists normal to the direction of flame spread. We present experimental and numerical results for flame spread through propanol-air layers formed near the flash point temperature (25 °C) or near the stoichiometric temperature (33 °C). Both the model and experimental results show that the removal of gravity results in a faster spreading flame, by as much as 80% depending on conditions. This is exactly the opposite effect as that predicted by an earlier model reported in [4]. We also found that having a gallery lid results in faster flame spread, an effect more pronounced at normal gravity, demonstrating the importance of enclosure geometry. Also reported here is the beginning of our spectroscopic measurements of fuel vapor.

## EXPERIMENTAL APPARATUS

The experimental rig, described more fully in earlier papers [1,2,3], consists of a porous bronze fuel holder 76 cm long by 10 cm wide by 3.2 mm deep, inside a thermally controlled tray that is covered by a stainless steel lid and Lexan gallery. The gallery has a 10 cm square cross section and can have either open or closed ends and top (one or the other is always open). The lid retracts automatically, and after a predetermined time for fuel vapor to diffuse and form a stratified, flammable boundary layer, a flame is ignited at one end and spreads to the opposite end of the gallery. We use the same rig for the microgravity experiments in the NASA Glenn 2.2s Drop Tower, with ignition and flame spread after release. A separate, but similar apparatus is used in normal gravity along with a Michelson interferometer to measure the fuel vapor concentration before and during flame spread [5].

In newly initiated research we have begun to measure the infrared spectrum of methanol as part of adopting a spectroscopic technique for its detection that is suitable for drop tower tests. A Fourier Transform Infrared (FTIR) spectrometer records training spectra in a range of conditions including temperature, methanol concentrations, and water concentrations. We designed and built a heated sample cell that allows temperatures of 500 °C to be achieved. A chemometric analysis will be used to correlate the spectral data with concentrations and temperature and to identify the optimal spectral window of a few wavenumbers.

## NUMERICAL MODEL

The model used in this work was originally developed for studying flame spread across sub-flash liquids, primarily 1-propanol and 1-butanol [6]. Previous references give much more

detail; here only a summary is given. The numerical model uses the SIMPLE algorithm [7] and a hybrid-differencing scheme to solve the gas-phase continuity, species, energy, x-y momentum equations and the liquid phase energy and x-y momentum equations. To simulate the experiments, the model initially runs for a specified time period (e.g. 60 seconds) without introducing the ignition source. During this period, a time step of 5 ms is used. This allows the fuel to vaporize at the pool surface and diffuse into the gas phase, setting up initial conditions consistent with the experiments. The output from the non-reacting case becomes an input to the reacting case. Reference [3] contains a diagram and further description of the model.

For the work reported here, we made three primary changes to the model. One, we changed the gallery dimensions to closely match the experiment. Two, modifications to the temperature-vapor pressure relationship produced better agreement with both the literature's vapor pressure data and our experimental flame spread results at temperatures above the flashpoint. Three, the effect of the porous bronze fuel holder was accounted for by modifying the liquid phase density, specific heat and thermal conductivity to be closer to that of bronze using a weighting formula.

## RESULTS

Figure 1 shows the flame position as a function of time, as determined from the video record for representative cases of 1-propanol at 27 °C. The slope of the experimental data yields the flame spread rate. As can be seen, the flame spread rates are steady, with the microgravity flame spreading faster. Also shown on the graph are the results for the numerical model, which are obtained until a steady flame spread rate is achieved. These data also show a difference between 1g and  $\mu$ g spread rates, but further work needs to be done to obtain better agreement with the experiments, and to check the spread rate for longer times.

Figure 2 contains a summary of our experimental propanol data for various diffusion times at 27 °C, in normal and microgravity both with and without a lid. As can be seen, there is some variation in the data (the uncertainty is similar to that found in the literature), and therefore several—usually four—nominally identical tests were conducted at each condition to achieve a good average. Once averaged, the results clearly show an effect of gravity level, with the flame spreading faster in microgravity, especially at longer pre-ignition diffusion times. This is true regardless of the presence of a lid on the gallery, which has the effect of increasing the flame spread rate. For a 60 s diffusion time, the  $\mu$ g flame spread 81% faster with the lid off, and 63% faster with it on, compared to 1g. At 35 °C (not shown) the 1g/ $\mu$ g flame spread rates were much closer, varying by about 15% with the lid off, and being essentially identical with the lid on.

Prior to ignition, the predicted mole fraction contours are essentially horizontal lines (except near the ends of the gallery where vapor spill-over occurs). In Figure 3 we show the predicted fuel mole fraction after ignition for a 1g case. As can be seen, the flame pushes the fuel vapor upwards as it approaches, increasing the effective flammable layer thickness. The work of [8] reports a similar displacement of fuel for methane layers along ceilings. This plot also shows the nature of the predicted double flame (a triple flame with the lowest branch quenched), with the premixed flame along the front and top, a non-combustible region in the middle, and a diffusion flame burning along the fuel surface where excess oxygen meets evaporating fuel vapor.

Figure 4 shows a similar plot as deduced from interferometric measurements in normal gravity at the same conditions as Figure 3. The molar refractivity of 1-propanol was not available to us, but we used a value of 18 based on comparisons of methanol/methane and ethanol/ethane values reported in [9] for the calculations. The agreement is good between model and experiment, with both showing roughly the same flammable layer thickness and the effect of fuel layer displacement by the flame. What is not as well predicted is the flame thickness (as deduced from the contour lines becoming disrupted), which is clearly larger in the experiment.

As part of the solution procedure the numerical code calculates the pressure; Figure 5 reports these results for both 1g and  $\mu$ g. The contours have been color coded for ease of interpretation, with darker (blue) regions being lower pressure, and lighter (redder) regions being higher. It is clear that one major difference between the 1g and 0g flame, as predicted by the model, is that in the  $\mu$ g case the flame is spreading into a region of lower pressure, while just the opposite is true in 1g. The difference between the highest and lowest pressure is about 47 Pa in both cases; this difference may contribute to the higher flame spread rate in  $\mu$ g.

For the spectroscopic measurements, a preliminary spectrum in Figure 6 shows two possible candidate intervals for methanol detection; one in the 7191  $\text{cm}^{-1}$  region; the other in the 7195  $\text{cm}^{-1}$  region as measured by our FTIR. The two methanol peaks are relatively large compared to the water peaks and relatively sharp compared to other methanol peaks in this region. The 7195  $\text{cm}^{-1}$  region is most preferable since it contains both methanol and water information.

## CONCLUSIONS

We have shown flame spread through non-homogeneous gas layers can be up to 80% faster in  $\mu$ g as compared to 1g. Both experiments and a numerical model have demonstrated this phenomenon. Further work needs to be done on obtaining quantitative agreement between the model and experimental flame spread rates; in particular we have initiated changes in the vapor pressure model and added heat loss to a bronze fuel holder. We obtained good agreement in the fuel vapor mole fraction predictions and measurements in 1g, and numerical results showed little difference in  $\mu$ g. Therefore, the faster flame spread rate in  $\mu$ g may be due to another effect, that of pressure, which we have begun to explore via the model and planned measurements. To make fuel vapor measurements in  $\mu$ g, we have also begun methanol spectrum measurements.

## ACKNOWLEDGEMENTS

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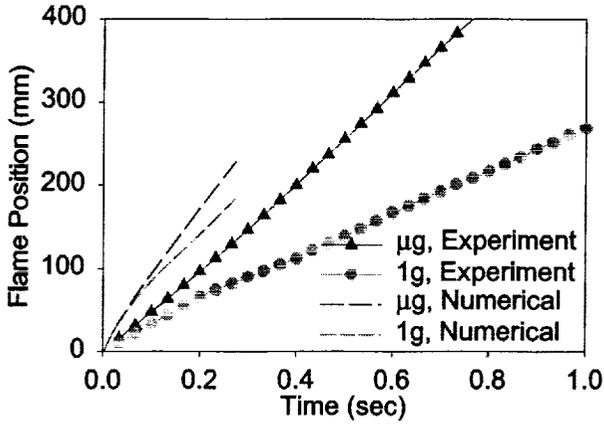


Figure 1. Flame position vs. time with a 60 s diffusion time for propanol in normal and microgravity, with the gallery lid off. Initial fuel temperature is 27 °C.

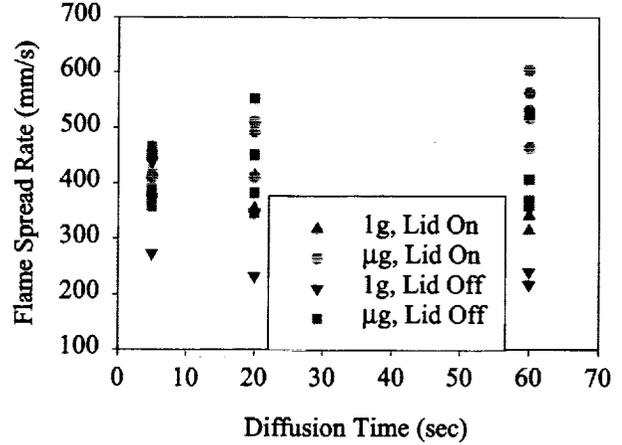


Figure 2. Summary of propanol tests with the gallery lid on or off. The data symbols represent the results of individual experiments.

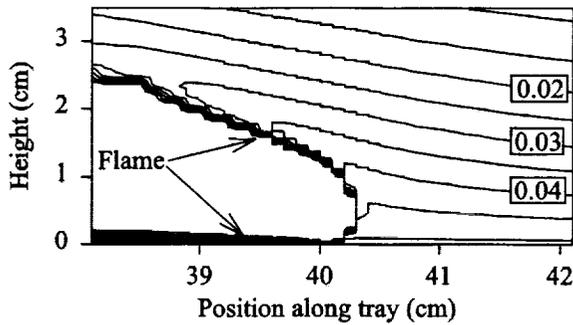


Figure 3. Numerical results of fuel vapor mole fraction at 35 °C and 60 second diffusion time.

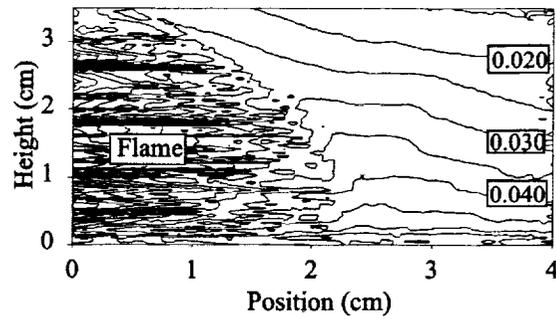


Figure 4. Experimental results for fuel vapor mole fraction at 35 °C and 60 s diffusion time.

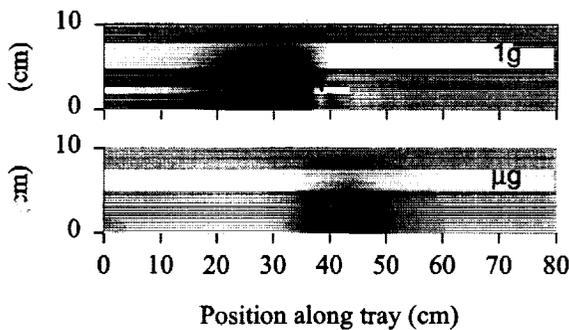


Figure 5. Pressure field in 1g and  $\mu$ g, 35 °C, 60 s diffusion time. Darker regions are lower pressure. Flame is at 40 cm in 1g, 43 cm in  $\mu$ g.

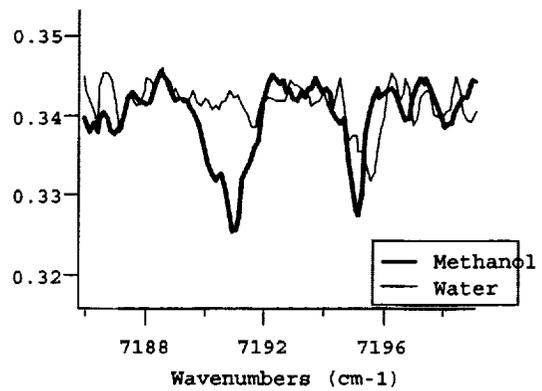


Figure 6. Methanol and water spectra. Vertical axis is proportional to transmission.